SSL SCIENCE CHALLENGES ROUNDTABLE

Droop in LEDs: Origin and Solutions

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Outline

- ✓ Why is it important to master droop?
- ✓ Why present techniques do not allow to identify the mechanism responsibe for droop?
- ✓ Identifying Auger recombination as responsible for droop through the electron emission technique
- ✓ Going further: finding solutions for diminishing droop

Why go for the few last efficiency %?

-Why absolute efficiency matters: needed to displace high efficiency fluorescents and HIDs, which produce the vast majority of Lumens today.

-Why are the last % are essential: improvement is non linear if thermal load is the limiting factor (also diminishes need for complex cooling architectures, thermal droop & improves reliabilty).

	WPE = 40%	WPE = 60%	WPE = 70%	WPE = 80%
If heat extracted from lamp sets chip power limit	20W	20W	20W	20W
Heat % of input power: 100% - WPE	60%	40 %	30 %	20 %
Total input power	33.3 W	50 W	66.6W	100 W
Light output: (input) – (heat)	13.3 W	30 W	46.6W	80 W
Relative power compared to 40% LED	0%	225 %	350 %	600 %

Why do we need to understand efficiency droop?

Current efficiency Droop is a major limiting factor in SSL

- It is raising costs. It leads to the use of many LEDs in a single lamp to keep efficiency high. It puts contraints on optics and reduces design space; it increases thermal load.

- It is enhanced for green LEDs: Is the droop mechanism somewhat associated with the green gap ? *Droop in the green has to be solved as Green LEDs are essential if we want RGB LED lighting, with the flexibility and adaptiveness it allows.*

- Thermal droop: Requires high performance heatsinking. What is its mechanism and is it related to efficiency droop? .

-In those structures where droop is stronlgy reduced (very thick active layers with many QWs, or DHs), semipolar or non polar structures, what is the mechanism of residual droop?

Understanding & directly measuring droop allows to optimize remedial solutions

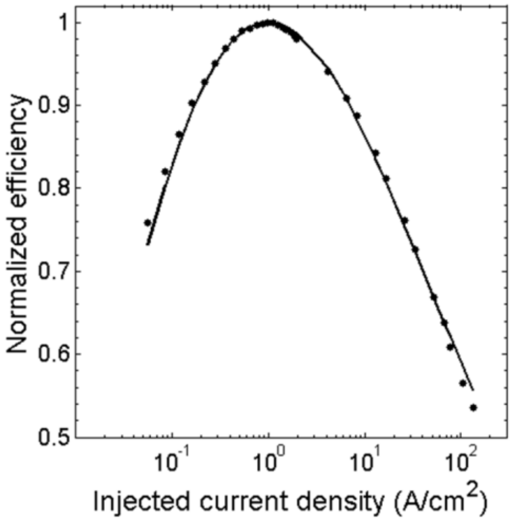
Present technique to identify droop mechanisms is not satisfactory: the ABC model

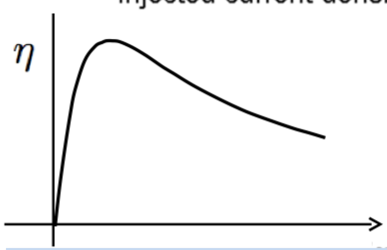
Mainly analysis of droop curve EQE vs. current density

The **ABC** model of recombination rate

$$J/e = R = A_{SRH}\, n_{QW} + B n_{QW}^2 + C n_{QW}^3$$

$A_{SRH}\, n_{QW}$	$B n_{QW}^2$	$C n_{QW}^3$
Non radiative Defects related	Radiative recombination	Non radiative - Auger - Current leakage -density-activated defect Recombination (DADR) - Carrier overshoot (non capture by QWs)





Efficiency:

$$\eta = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

d active (# QWs)	B $10^{-12}cm^3 s^{-1}$	A $10^{-6} s^{-1}$	C $10^{-30}cm^6 s^{-1}$	n peak 10^{17} cm^{-3}
1	20 1)	2.82	3.60	8.8
1	7.9 2)	1.77	0.89	14
1	100 3)	6.30	**40.3**	3.9
8	20	0.996	10.2	3.1
8	7.9	0.626	2.53	5.0
8	100	2.23	**114**	1.4

1) Zackheim, Phys. Stat. Sol. A 209, 3, 456 (2012)

2) David, APL 97, 033501 (2010) **measured**

3) Schubert, APL 97, 133507 (2010)

Note the huge ranges of A and C values obtained by ABC fitting of left EQE curve, for three assumed values of B, and assuming either 1 or 8 excited QWs.

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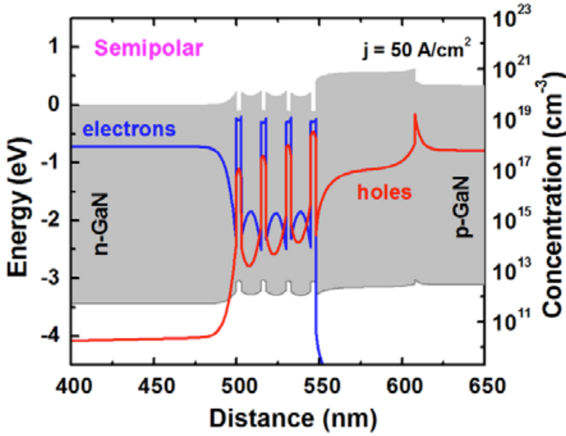
Present technique to identify droop mechanisms is not satisfactory

Major difficulty: ABC analysis looks at LED as an homogeneous system

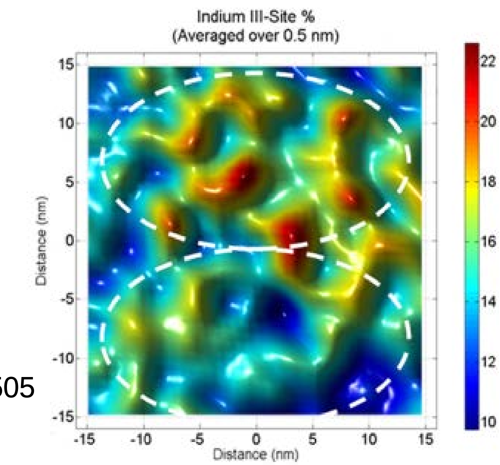
But there are several major sources of inhomogeneity



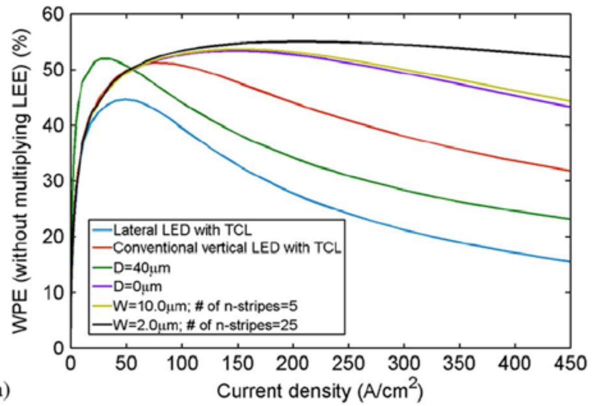
STR group
SiLENSe software

-Injection inhomogeneity (except single QWs): holes are more concentrated in MQWs near the p contact layer- changes with current

-Compositional fluctuations: carriers are concentrated in potential minima



Yuh-Renn, Speck et al.
Appl.Phys. Lett. 101, 083505 (2012)



(a)

-Current crowding : carriers are concentrated near electrodes- therefore diminishes Light extraction efficiency (LEE)and increases droop by increased local concentrations

Chi-Kang Li and Yuh-Renn Wu
IEEE Tr. El. Dev.. 59, 400 (2012)

In addition, A, B and C change with current density due to the screening of the internal electric fields.

Present technique to identify droop mechanisms is not satisfactory

Inhomogeneity of carrier densities and density induced changes induce huge variations & uncertainties in ABC extracted parameters for similar materials because of different LEDs active layer designs and LED & contact geometries

Technique can be useful for comparison purpose of similar structures

But identification of any droop mechanism , based on value and variations of C parameter on LED structure design, is highly questionable

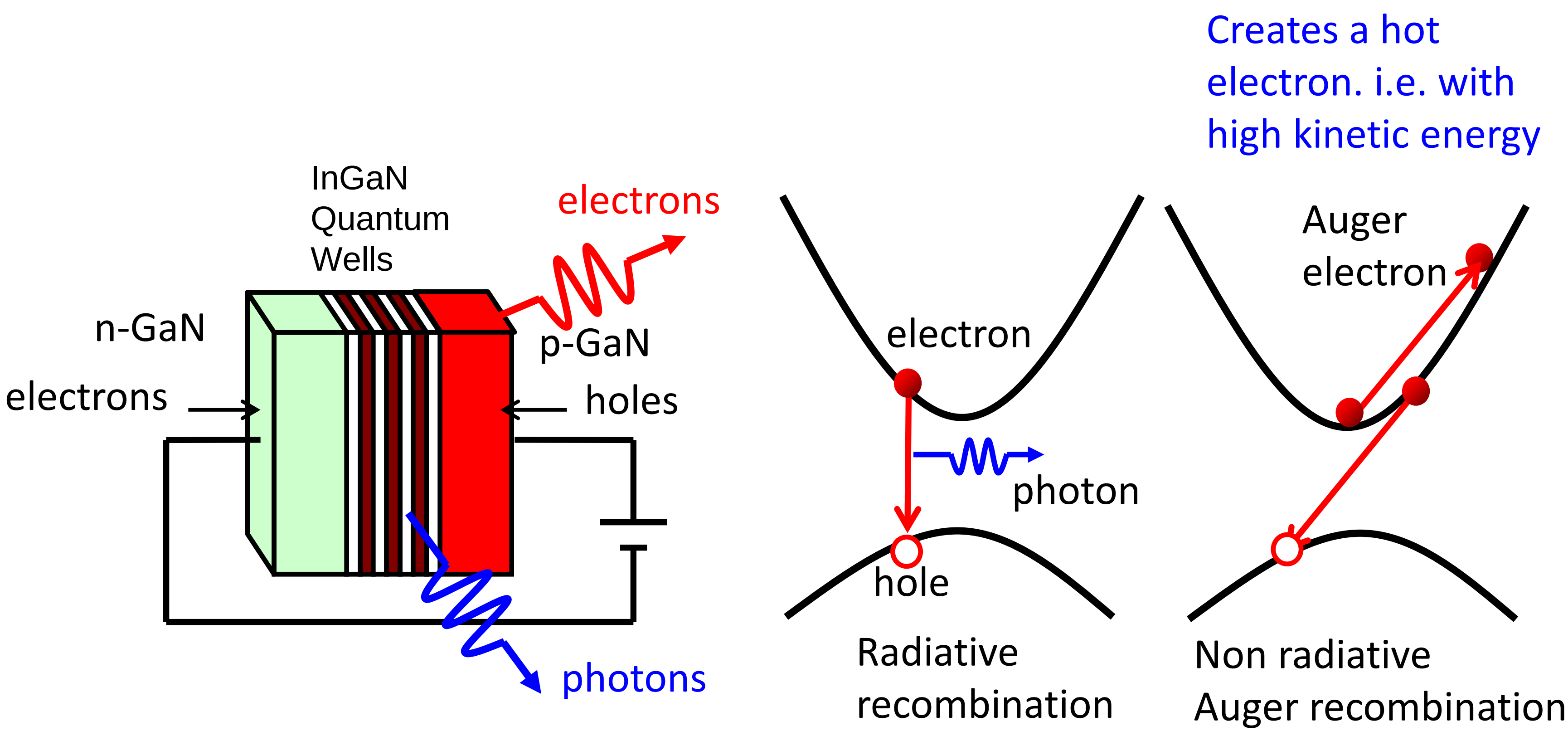
Better experiment than LED injection: droop & C measurements by optical excitation (thus no current crowding, no current leakage, uniform excitation), based on lifetimes and photoluminescence measurements, but then it is not really representative of LED operation.

Temperature studies not much help as many things change, beyond the ABC coefficients: localization, hole injection, electron injection (if limited by overshoot), conductivity (mainly holes), current crowding, ec.

Common cures of droop cannot lead to identification, as these cures are efficient for any of the mechanisms (Auger, carrier leakage, etc.), by decreasing carrier density.

e.g. increased QW #, changed QW & barriers composition or thickness, polarization matched AlInGaN MQW barriers, partial polarization matching, reduced barrier height in MQWs, thick DH active layer, …

Focus on a favoured droop mechanism: Auger recombination process



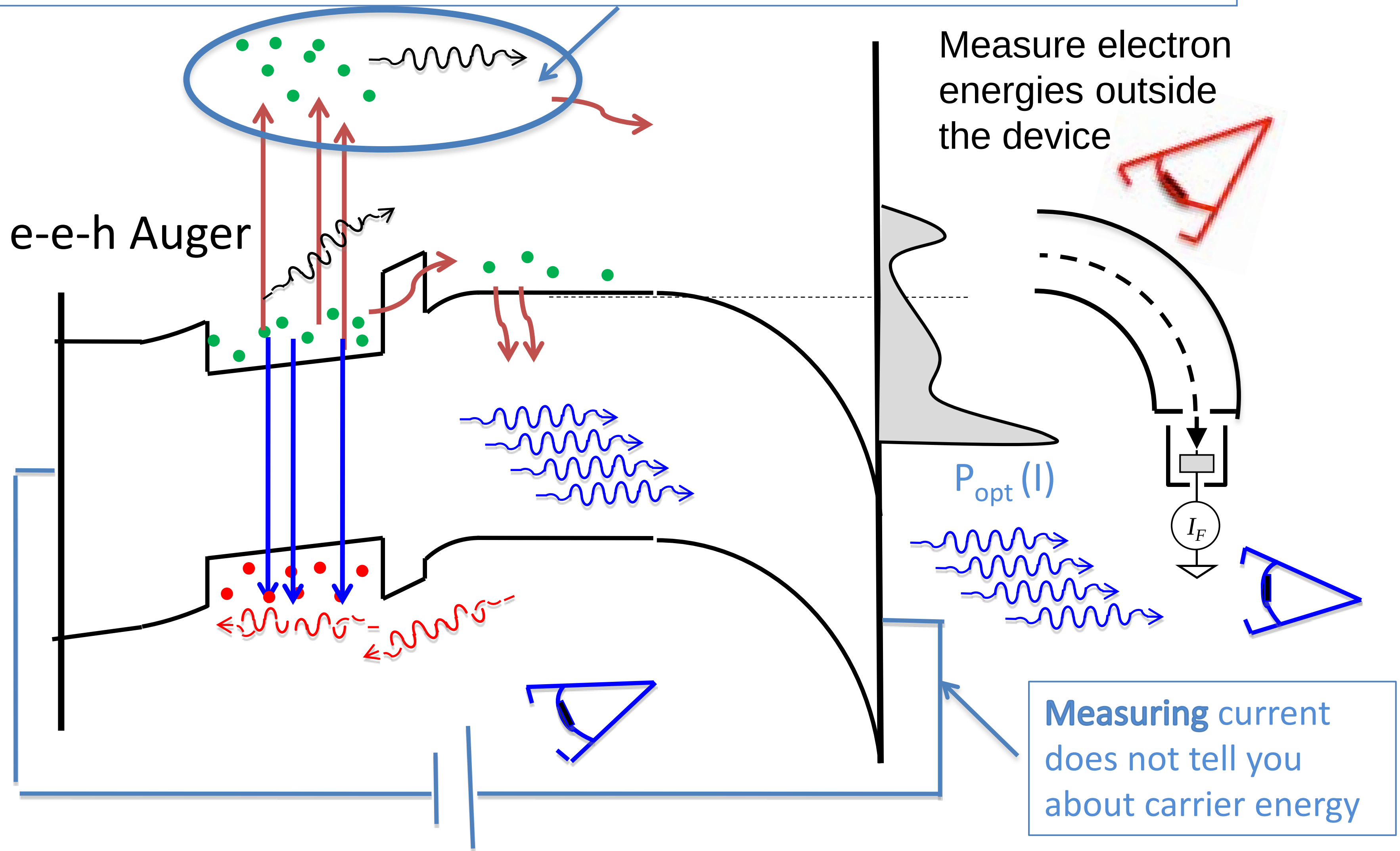
The signature of an Auger process is the generation of electrons with high kinetic energy

Theory: direct Auger process probabiltiy is small, but phonon assisted Auger is of the order of a few $10^{-31} cm^6 s^{-1}$

Kioupakis, Rinke, Delaney, Van de Walle, APL 2011

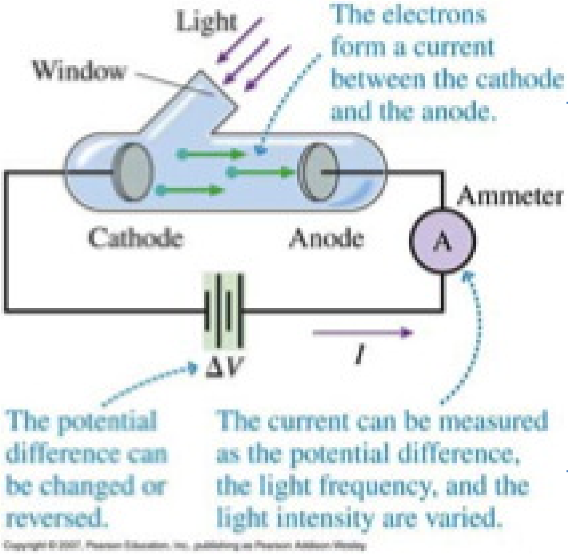
A new technique to directly observe Auger recombination as the droop mechanism

If there is Auger recombination , you should see hot electrons

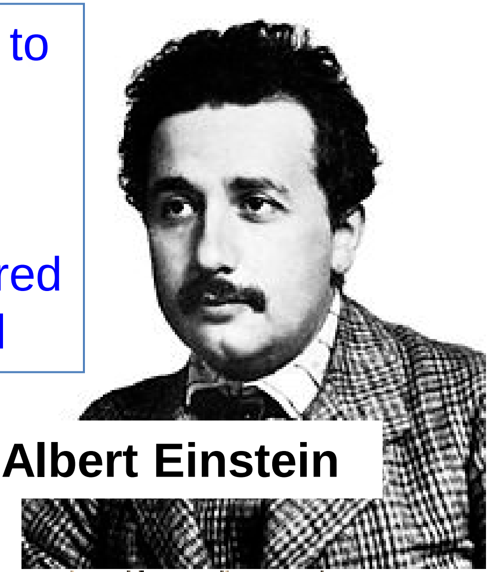


Measuring electron energy outside materials: an old story
The photoelectric Effect (Hertz, 1887)

Light quantization 1905



- Electrons are ejected from metal due to photoexcitation.
- Through ejection they conserve their kinetic energy
- Ejected electron energies are measured using a retarding/accelerating potential

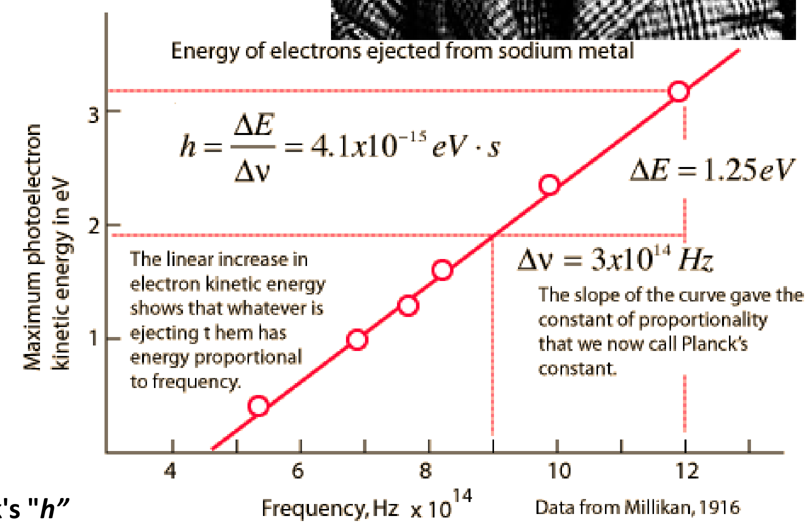


Albert Einstein

Measurement of Planck's constant 1916

Robert Millikan

R.A. Millikan Phys. Rev. 7, 355–388 (1916)
"A Direct Photoelectric Determination of Planck's "*h*"



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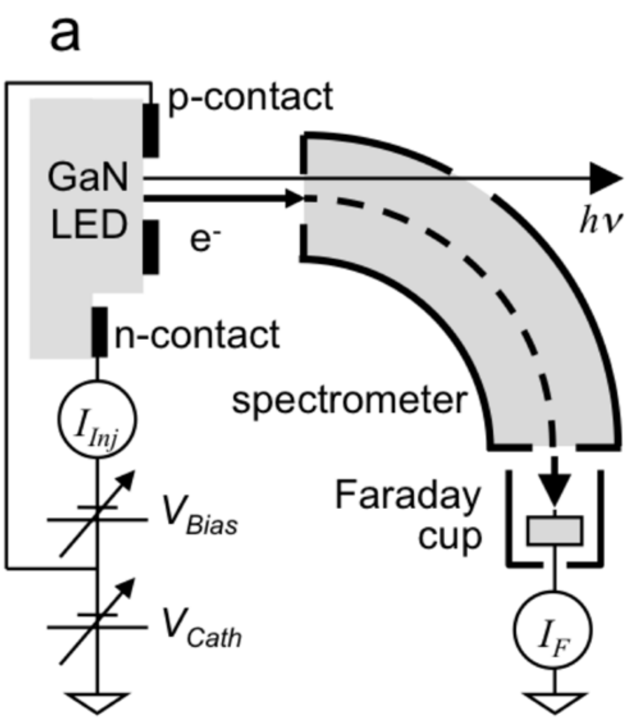
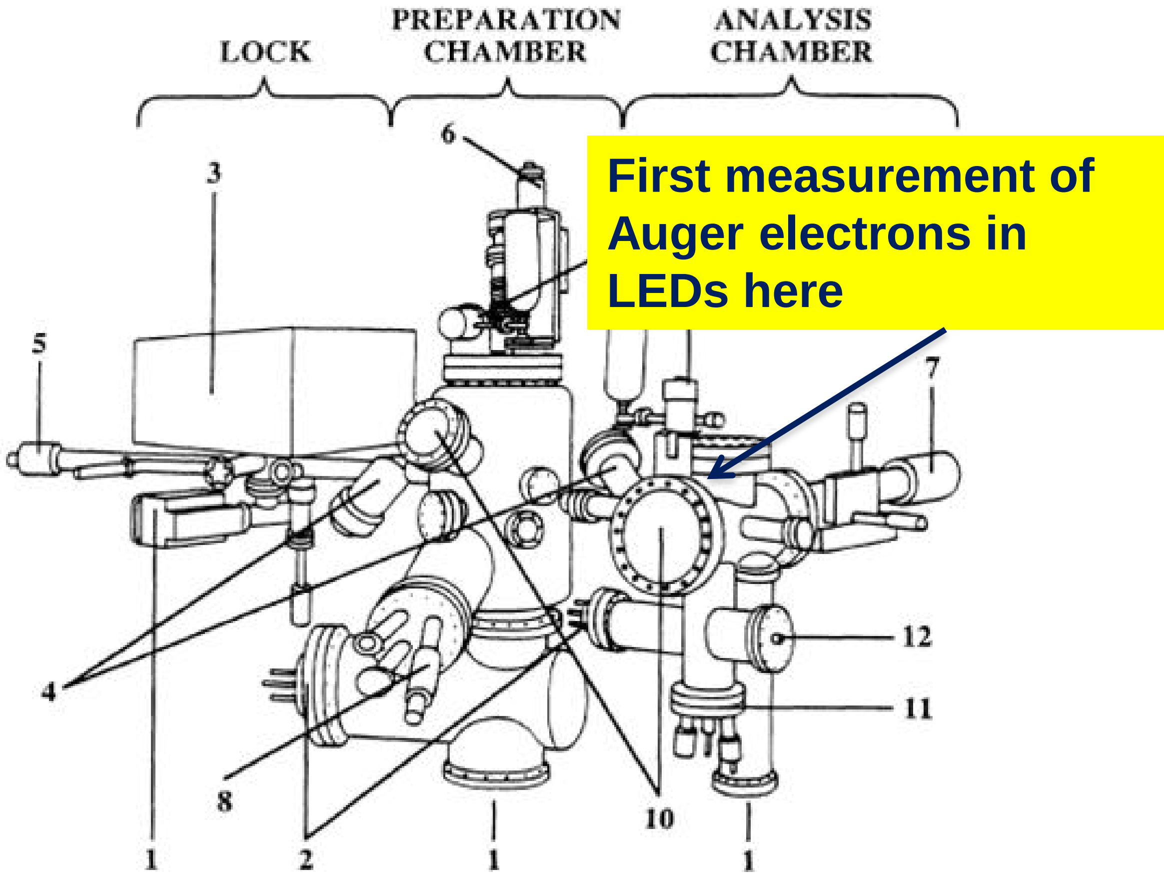
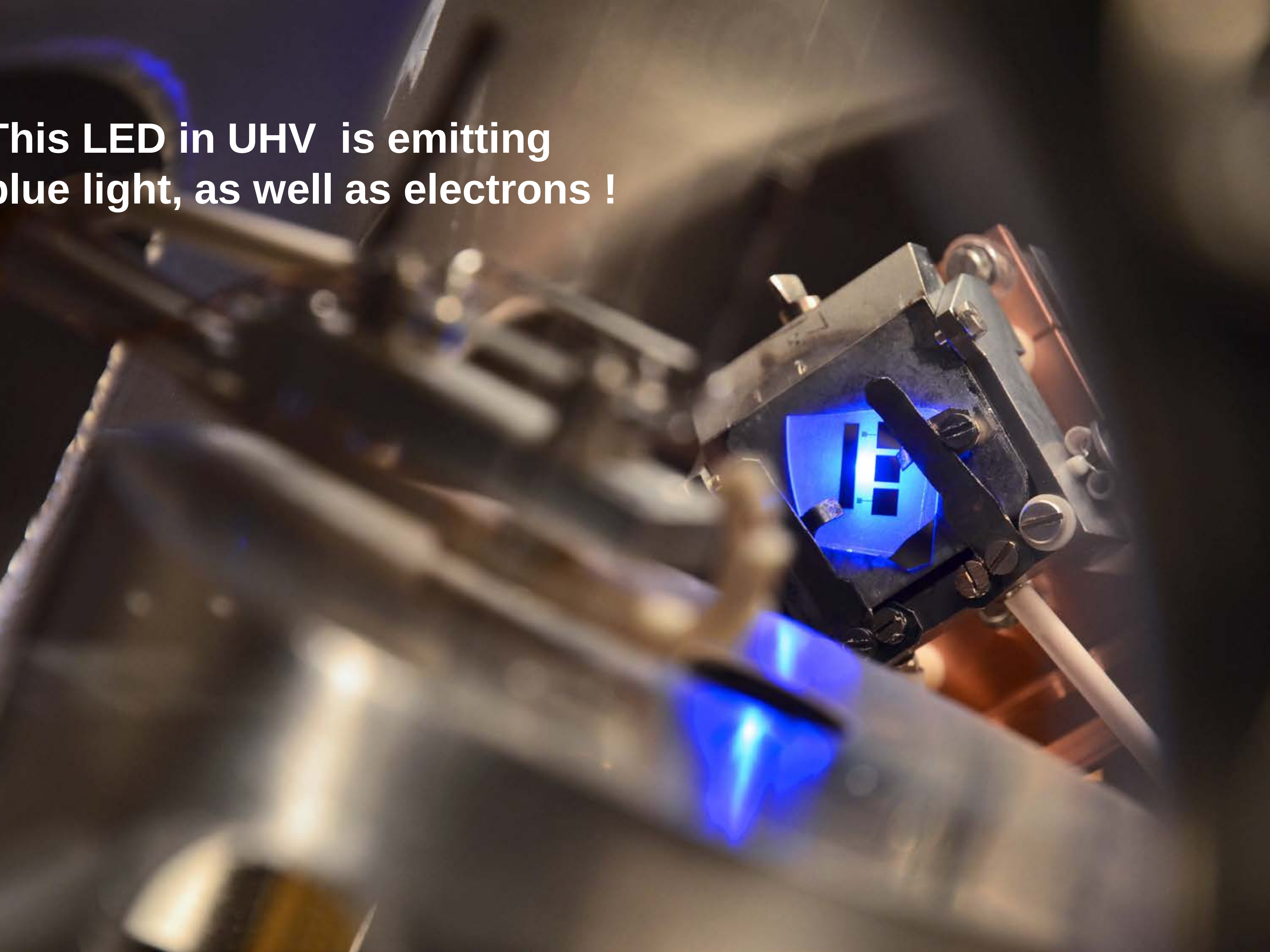
A new technique to directly observe Auger recombination as the droop mechanism



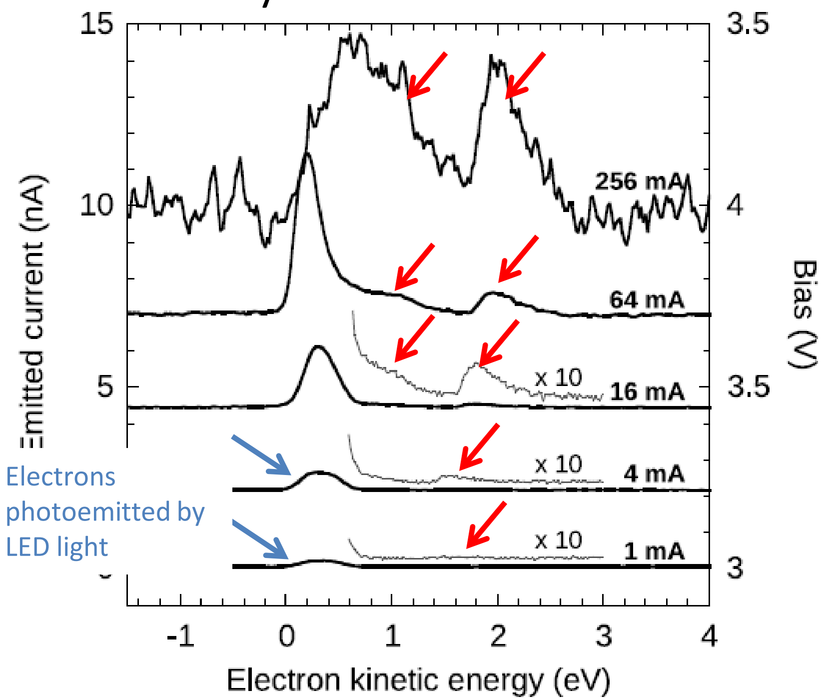


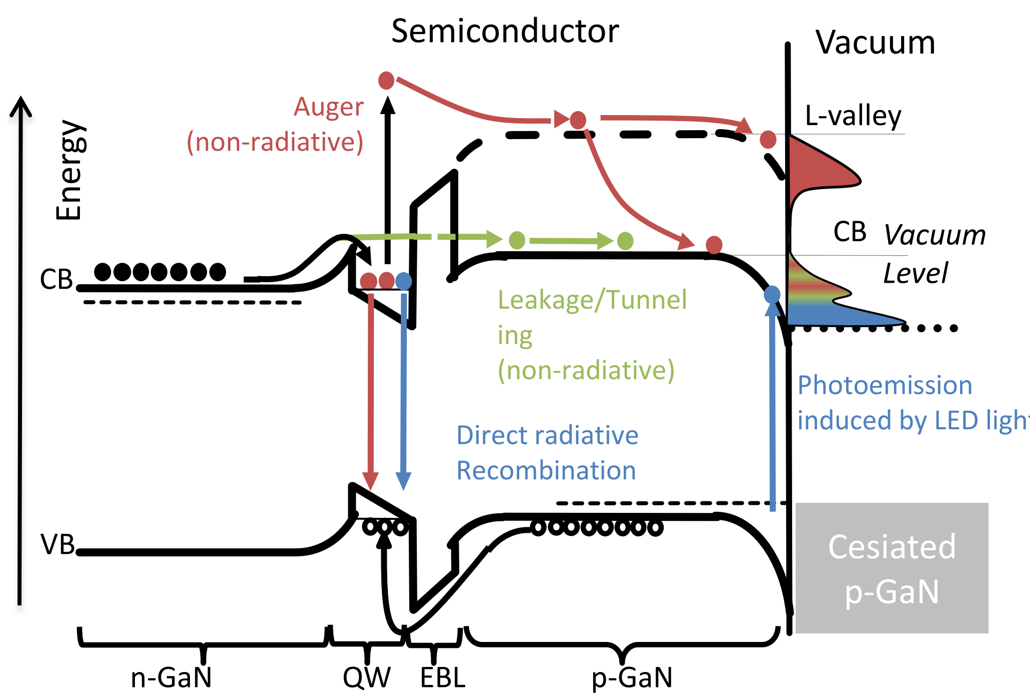
J. Iveland et al., "Direct Measurement of Auger Electrons Emitted from a Semiconductor Light-Emitting Diode under Electrical Injection: Identification of the Dominant Mechanism for Efficiency Droop", Phys. Rev. Lett. 110,177406 (2013)


This LED in UHV is emitting
blue light, as well as electrons !

Relation between outside electrons, emission efficiency, droop current

Under high current injection, high kinetic electrons appear, which can only be generated by Auger effect in the LED as there is no high electric field or large energy barrier discontinuity in the structure



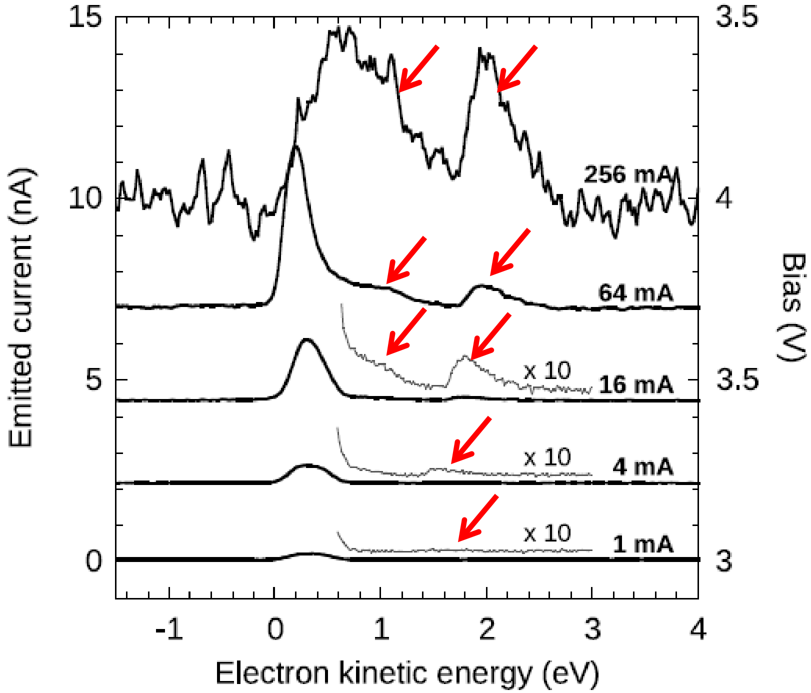


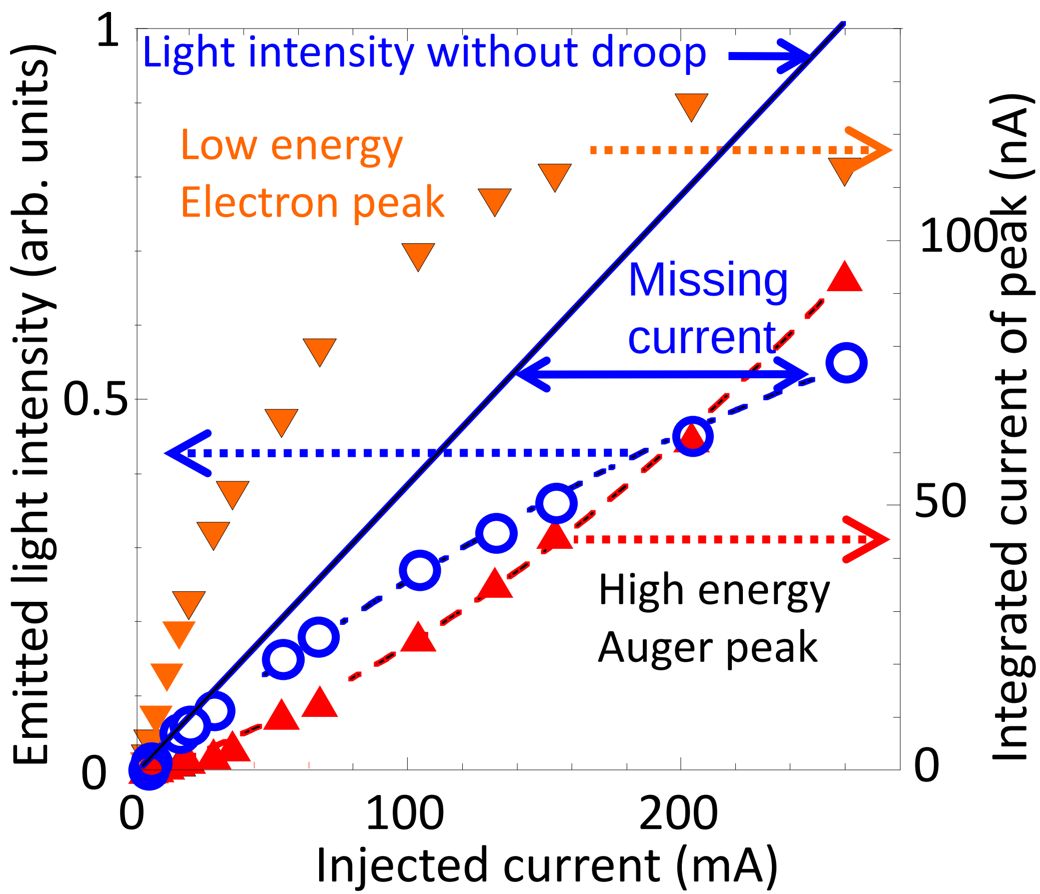
•Pulsed measurements (reduce heating)
•Field distortion at high current reduces signal

Relation between outside electrons, emission efficiency, droop current

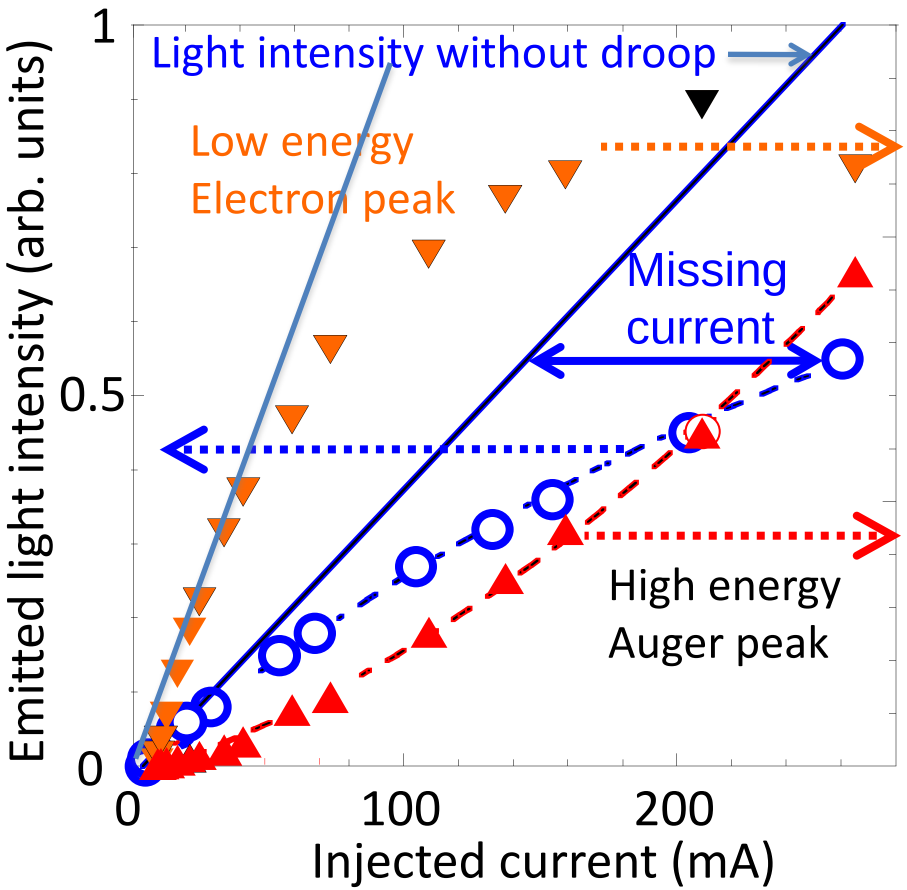
The light intensity droops (blue circles and dashed blue curve), as well as the low energy electron peak current yellow (triangles), as these electrons are due to photoemission by the LED light.

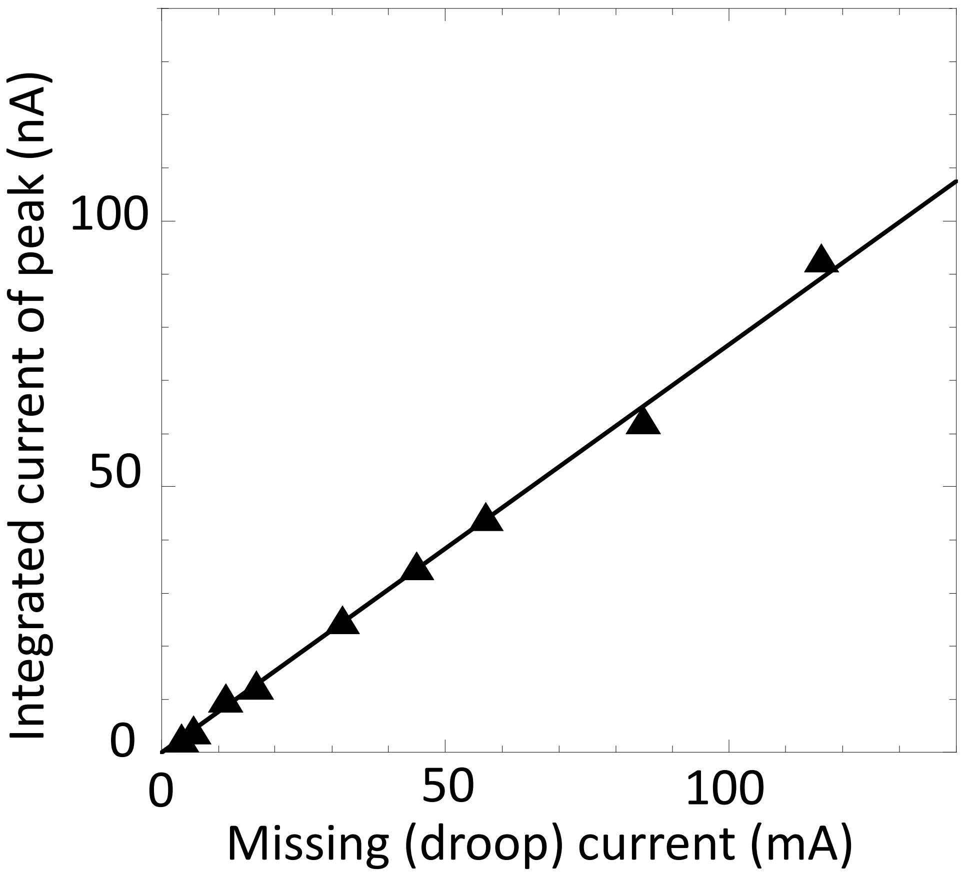
The high energy electron current increases superlinearly, as it is fed by the droop current.





Correlation between Auger current (in vacuum) and droop current (in LED)





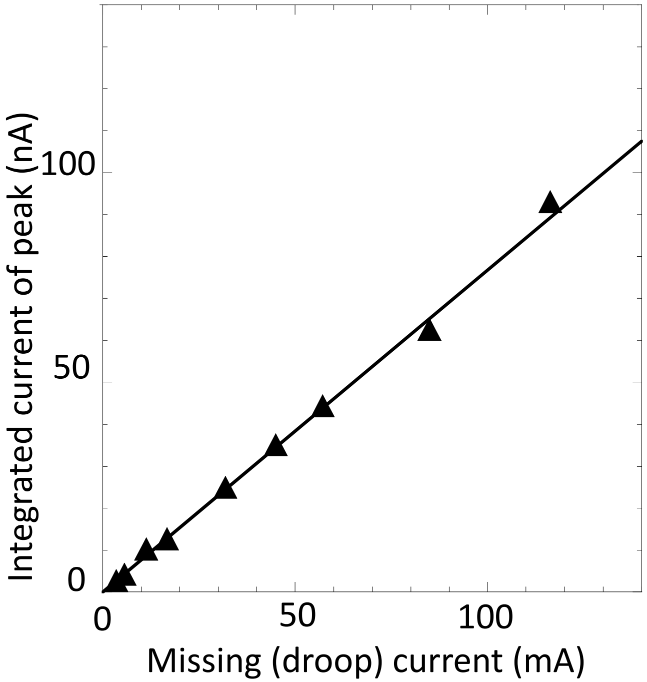
Integrated intensity of high energy peaks (Auger- n^3) scales linearly with missing droop current: they have the same functional dependence on carrier density – Thus missing current is due to Auger effect as other droop mechanisms do not scale as n^3

Correlation between Auger current (in vacuum) and droop current (in LED)

Advantages of having an independent measurement of droop through the external Auger current

- You measure externally the droop current and its mechanism independently of carrier injection, current crowding, compositional inhomogeneities, and of electric field screening, with no curve fitting.

- You can then assess the effect of curing measures on the Auger effect, and differentiate from other phenomena.



The technique allows to also determine many of the operating mechanisms of LEDs,such as electron overshoot, carrier leakage, electron blocking layer efficiency, …

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The future: how to solve the droop issue in LEDs, from the capacity to measure the droop mechanism

- Blue c planes LEDs: (i) compare designs and their droop performance: (ii) go to *ultrathin barriers* to have uniform injection; (iii) control *current crowding*; (iv)*Structures with many QWS* have excellent carrier collection from solar cell studies, including holes. How do they perform in LEDs and would they indeed display low droop? (v) *Evaluate EBL efficiency.* Can we remove EBL? (vi) Measure *quantitatively leakage and overshoot* of electrons.

- m plane and semipolar LEDs : *is the residual droop due to Auger? What are the origins of the vastly different droop sizes along different axes ?*

- c-plane green LEDs: is the strong droop due to larger QCSE or is it mainly related to larger compositional fluctuations? Design structures to address either of the mechanisms.

- Thermal droop: *origin? Is it related to Auger*? Optimize structures for it.

Thank You!